The Engineering Behaviour of a Canadian Muskeg

Le Comportement technique d'une tourbière canadienne

J. I. ADAMS, *Supervising Engineer, Soils Section, Research Division, Hydro-Electric Power Commission of Ontario, Toronto, Canada*

SUMMARY

The engineering behaviour of a Canadian muskeg was studied both in the laboratory and in the field. It was shown that the strength of the peat was essentially frictional and that its permeability varied widely during consolidation. Two distinct stages of consolidation were observed, a short-term stage which is believed to be the expulsion of free pore water in the peat, and a long-term stage which is believed to be the compression of the solid peat matter. Long-term pore pressures were observed which are believed to be associated with the compression of the solids.

SOMMAIRE

Le comportement technique d'une tourbière canadienne a fait l'objet d'études tant en laboratoire que sur le terrain. De ces études, il ressort que la résistance de la tourbe est essentiellement une résistance de frottement et que sa perméabilité varie considérablement durant la consolidation. Deux étapes distinctes de consolidation ont été observées, l'une à court terme qui, croit-on, est l'expulsion de l'eau capillaire libre, et l'autre à long terme qui, croit-on, est la compression de la tourbe solide. On a observé des pressions capillaires à long terme et l'on pense qu'elles sont associées à la compression des solides.

"MUSKEG" IS ORGANIC TERRAIN which has resulted from the incomplete decomposition of surface vegetation. It consists of dead and fossilized organic matter known as peat supporting a surface layer of living vegetal matter. The living layer ranges in consistency and stature from grasses and mosses to relatively high bushes and trees. Although peat is by nature fluid and compressible, its properties are variable and are largely determined by the living matter from which it originates. The correlation of the living layer with the co-existing peat layer was observed by Radforth (1952) and formed the basis of his engineering classification of muskeg. Although muskeg is found in many parts of the world, its presence in the northern hemisphere is most noticeable in northern Europe, the U.S.S.R., and Canada. In Canada, as will be seen in Fig. 1, muskeg covers more than 50 per cent of the land surface south of the tree line, and its presence has presented formidable obstacles to the development of natural resources in the north. In the development of hydraulic power sites in northern Ontario, problems associated with muskeg determine to a large extent the economic feasibility of many potential power projects.

FIG. 1. Map of Canada showing areas of muskeg occurrence.

Studies of the engineering properties of peat were undertaken by the Ontario Hydro Research Division in 1960. Initial laboratory tests included those of consolidation, permeability, and triaxial compression. Instrumentation of peat underlying several embankments has been carried out, and an attempt has been made to relate field to laboratory behaviour. Although much of this work has been presented earlier (Adams, 1961, 1963), the results of all of the work, including some recent laboratory studies, are now presented and reviewed. The behaviour of peat with respect to strength and compressibility is discussed, and general concepts are suggested which may be helpful in predicting the engineering behaviour of muskeg.

LOCATION AND CLASSIFICATION OF MUSKEG

Studies of muskeg were made at three locations in the Moose River basin, as shown in Fig. 1. The muskeg-cover classification and the results of physical tests on the peat at the three locations are shown in Table I. At each of the locations shallow embankments were constructed on muskeg for the purposes indicated in the table. Instrumentation of the peat foundations was carried out and measurements of settlement and pore-pressure development were made during and subsequent to construction. "Undisturbed" bulk samples of the peat were obtained from each location and used in laboratory studies.

LABORATORY STUDIES

The literature reveals uncertainty as to whether peat behaviour is frictional or cohesive. Hanrahan (1954), for instance, held that the strength of peat was essentially cohesive. Others considered the possibility that the fibre tensile strength might influence peat behaviour. With respect

TABLE I. PHYSICAL PROPERTIES AND CLASSIFICATION OF PEAT

Location	Muskeg* cover	Peat*	w per cent dry wt.	G	pH	Ash per cent dry wt.
1 Little Long Rapids GS (access road	ADI/BEI	No. 9–11	200–600	1.62	4.8–6.3	12.2 to 22.5
2 Abitibi Canyon GS (sewage lagoon embankment)	FI/I	No. 2	355–425	1.73	6.7	15.88
3 Harmon GS (block dam)	DFI/B	No. 6–4	330–375	1.65	6.2	12.27

*Radforth classification (1952).

to the consolidation of peat, the observed behaviour was similar in most instances, but the interpretation of results varied from the opinion that the consolidation of peat was essentially "primary," to one that it was essentially "secondary."* All appeared to agree that settlement was continuous. A good example of the long-term behaviour of peat was given by Buisman (1936), who cited embankments on peat (Holland) in which continuous settlement, linear with the logarithm of time, was recorded for more than eighty years. Another consistent observation was that of the marked change in the permeability of peat with change in volume (see, for example Miyakawa, 1960). The testing described below was carried out with the hope of resolving some of the uncertainties.

Permeability Tests

Permeability tests were carried out on remoulded peat in an 8-in.-diameter settlement-permeability device. The peat was consolidated under successive increments of vertical compression. At the completion of each loading period the permeability of the peat was determined by a falling head test. Fig. 2 shows that the peat was initially quite pervious

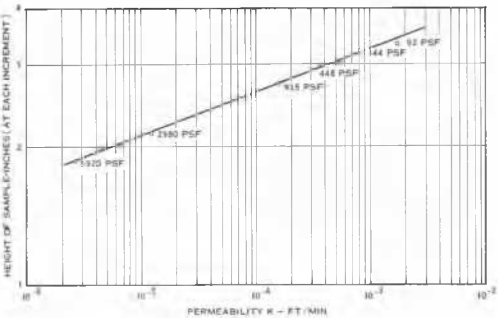

FIG. 2. Permeability *versus* sample height.

but became relatively impervious under high compressive loads. Of significant interest is the linear variation of the logarithm of k, the coefficient of permeability, with the logarithm of H, the thickness of sample. Similar findings were reported by Miyakawa (1960).

Strength Tests

Samples of peat were prepared from "undisturbed" bulk samples obtained at location 2. Undrained triaxial tests with pore-water–pressure measurements were carried out on samples which were saturated by back pressure and con-

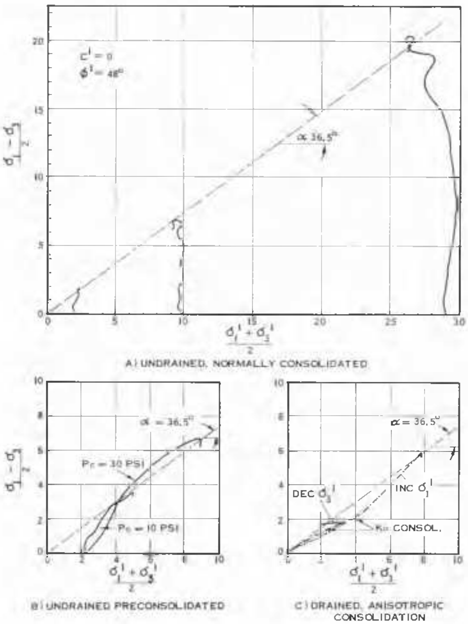

FIG. 3. Triaxial stress plots.

solidated isotropically under 2, 10, and 30 psi confining pressures. Two samples were unloaded after isotropic consolidation under 10 and 30 psi and tested at preconsolidation ratios of 5 and 15 respectively. Drained triaxial tests were made on two samples of peat which were consolidated anistropically (zero lateral strain) and then failed by increasing σ'_1 or decreasing σ'_3. Stress plots of all the triaxial tests are given in Fig. 3. It will be seen that in all tests the stress plots at failure (max σ'_1/σ'_3) fall generally on a single line through the origin, and that the angle of shearing resistance in terms of effective stress indicated from these tests is high ($\phi' = 48°$). Correction for rate of volume change was applied to the drained tests but the correction was found to be insignificant. The K_0 value of the peat for the two drained tests was calculated to be of the order of 0.3.* The preconsolidated samples showed a slight prestress effect but it would appear that this effect is minor for even highly preconsolidated material.

Consolidation Tests

Consolidation tests were carried out on samples from the three locations shown on Fig. 1. The thicknesses of

*"Primary" consolidation is considered here as that portion occurring mainly under an excess hydrostatic pressure, and "secondary," that portion occurring mainly under zero, or negligible hydrostatic pressure.

*Where $K_0 = \sigma'_3/\sigma'_1$ for zero lateral strain.

the samples are shown in Fig. 5. On the 8-in.- and 4.5-in.-diameter samples the excess hydrostatic water pressure was measured during the tests by noting the rise in water level in fine-bore plastic tubing connected to the base plates of the samples, drainage being allowed to the top surface.* The consolidation loads were varied from 30 to 2,000 psf, and were applied in single increments, as well as in multiple increments ($\Delta P/P = 1$).

The results of a typical test on peat are shown in Fig. 4 in which settlement and pore pressure are plotted to different time scales. In each time plot (arithmetic, square root, and logarithm) it will be noted that there is an initial settlement, S_0, occurring in a relatively short period of time ($t_0 = 5$ min). The settlement continues but at a much slower rate which is approximately linear with the logarithm of time. These results are reasonably typical of all tests carried out in the present study. It may be noted that the excess pore pressure was almost entirely dissipated during the initial consolidation period; a residual pressure of low magnitude (1 inch of water) remained, which decreased slightly with time.

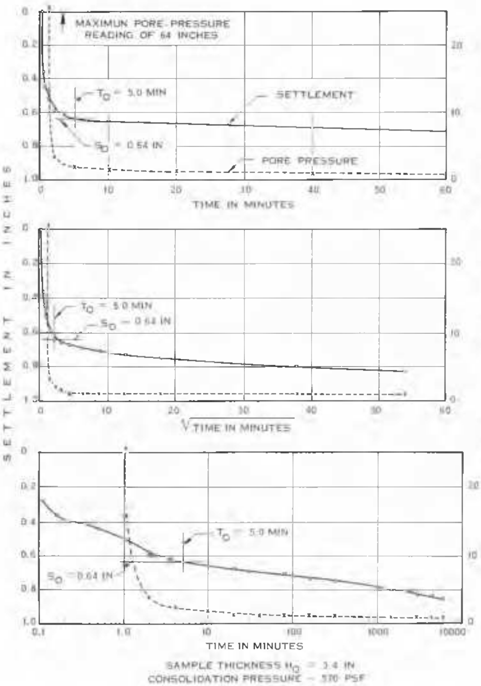

FIG. 4. Typical consolidation curve.

The initial settlement S_0 was calculated for each test and expressed as the ratio ($\Delta H/H_0$) (change in height over initial height). This value was plotted to the logarithm of the applied load as shown in Fig. 5. Although the points are scattered, they fall within a band indicating a general relationship between the initial compression of the peat and the magnitude of the applied load. It will also be seen that at higher pressures the relationship for the peat from location 1 differs from those for locations 2 and 3.

*The measurements are obviously in error during rapid volume change but are considered accurate when the rate of volume change is relatively low.

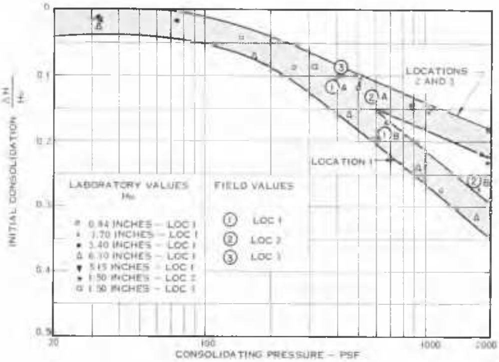

FIG. 5. Initial consolidation.

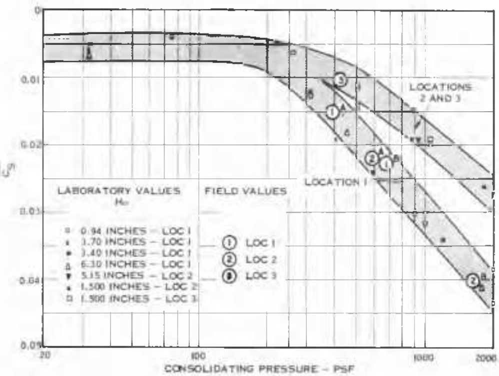

FIG. 6. Long-term consolidation.

It has been shown that the long-term consolidation of peat is generally linear with the logarithm of time. As the slope of this plot appeared to vary in a logical manner with both applied load and sample thickness, it was thought to be significant for relating laboratory and field behaviour. The concept was originally suggested by Buisman (1936) and was mentioned more recently by Miyakawa (1960). For all tests carried out, the slope of the long-term log plot was calculated and the value $\bar{C}_s$ was determined by dividing the slope value by the thickness of the peat ($H_0 - S_0$) at the start of the long-term compression. The $\bar{C}_s$ values plotted against the logarithm of the applied load are shown in Fig. 6. It will be seen that an approximate grouping was obtained indicating a general relationship for the rate of long-term consolidation with the magnitude of the applied load. Also, the relationship for the peat from location 1 differs from those for locations 2 and 3.

COMPARISON OF LABORATORY AND FIELD BEHAVIOUR

In each of the field embankments at the three locations indicated on Fig. 1, instruments were installed in the peat foundation prior to construction, and measurement of foundation settlement and pore-pressure development were recorded both during and subsequent to placing the embankment material. Descriptions of the sections instrumented are given in Table II.

TABLE II. DESCRIPTION OF FIELD SECTIONS INSTRUMENTED

Location	Depth of fill (ft)	Depth of peat (ft)	Muskeg classification	Description of underlying mineral soil
1A*	6.0	7.0	ADI	dense till
1B*	3.5	14.0	BEI/EI	dense till
2A	7.0	5.6	F/I	soft marl
2B	15.0	4.7	F/I	soft marl
3	4.4	8.1	DFI/B	dense till

*Corduroy mat used on top of muskeg.

During construction of each embankment a large settlement was recorded immediately on first application of load. By the end of the construction period the consolidation occurred at a much lower rate. Although the settlement was irregular it was believed to be essentially linear with the logarithm of time. The pore-pressure development was appreciable and in the case of the deepest peat (15 ft at location 1) approached the vertical unit weight of the embankment. In all cases the pore pressures appeared to be continuous. The settlement and pore-pressure measurements from the three locations were plotted to the logarithm of time (Fig. 7).

To compare the field consolidation with the laboratory consolidation, the immediate settlement expressed as $\Delta H/H_0$ was calculated from each of the embankments instrumented as well as the coefficient of secondary consolidation $\bar{C}_s$. These values were plotted on Figs. 5 and 6 to compare with the laboratory relationships. The $\bar{C}_s$ values shown cover a comparatively short period, the maximum period being about 1½ years at location 1. It will be seen that the field values of $\Delta H/H$ and $\bar{C}_s$, for locations 1 and 3, plot within the laboratory range. The field values from location 2 plot below the laboratory range. At this location, however, compressible marl was found underlying the muskeg, and the field values were calculated on the basis of the peat thickness only.

DISCUSSION

The consolidation of peat was observed in the laboratory and in the field to occur in two distinct stages. In an initial stage relatively large-magnitude compression occurs in a short period. The duration of the initial stage is in terms of minutes in the laboratory and in terms of days or weeks in the field, for the cases observed. A long-term stage follows in which the rate of settlement is much less and essentially linear with the logarithm of time. It was shown that the magnitude of the initial settlement was directly related to peat thickness and applied load, and that both field and laboratory measurements confirmed this general relationship. Further, it was shown that the rate of long-term consolidation could be related to peat thickness and applied load. This relationship also was confirmed by laboratory and field measurements although the latter cover a comparatively short period.

It has been shown that the permeability of peat decreases in a predictable manner with reduction in volume, and this behaviour is believed to be a significant characteristic of peat. Although not shown in the testing, it is believed that the solid constituents of peat contain a high percentage of water and are compressible. The following concept of the consolidation of peat is suggested and is based primarily on the above two assertions. On application of load, the free pore water in the peat is expelled under excess hydrostatic pressure. Since the peat is initially quite pervious and the percentage of pore water is high, the magnitude of consolidation is large and this period of consolidation is short. As the peat undergoes a large volume change the permeability is significantly reduced. During this period the effective consolidating pressure is transferred from the pore water to solid peat fabric in a manner similar to the primary consolidation of clay. Unlike mineral soil the solid peat is compressible and will sustain only a certain proportion of the

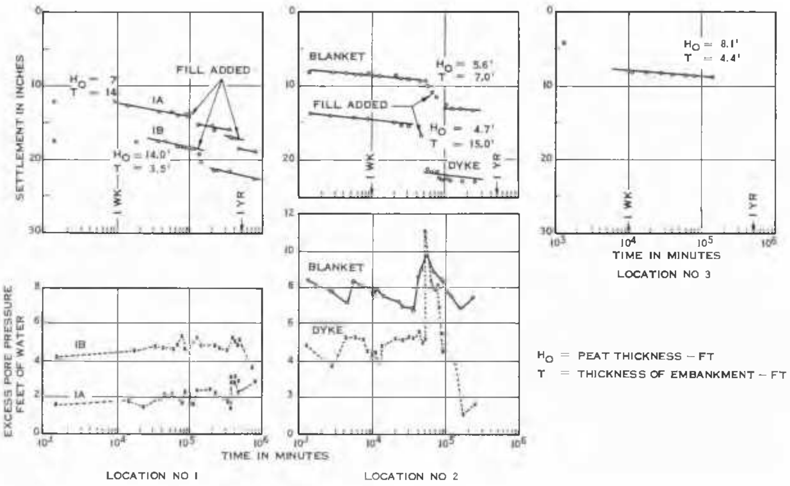

FIG. 7. Results of field instrumentation.

total effective stress, depending on the thickness and permeability of the peat mass. An equilibrium condition is eventually achieved when the rate of compression of the solid peat is the same as the rate of compression of the peat mass, at which time the pore pressure, or more probably the hydraulic gradient, becomes constant.

If the flow of water through peat is according to Darcy's law, i.e., $dH/dt = iK$, where the hydraulic gradient i is a constant, and the coefficient of permeability K varies with thickness according to the relationship shown in Fig. 2, i.e., $\log K/K_0 = C \log H/H_0$, it can be shown that H, the peat thickness, will vary approximately with the logarithm of time. The field and laboratory observations tend to support this concept.

CONCLUSIONS

The strength of the peat is shown to be essentially frictional and in accordance with the principle of effective stress. Although the behaviour of the peat is similar to that of granular material, it is only slightly dilatant even when highly preconsolidated. A somewhat unique characteristic of peat is an unusually low K_0 value. Since this value implies that appreciable shear stresses occur during normal consolidation, the magnitude of construction pore-water pressures is particularly significant in determining the stability of peat.

The consolidation of peat is shown to occur in two distinct stages: an initial stage which for most cases can be considered immediate and a long-term stage which continues indefinitely at a slow rate. General relationships for the magnitude of the initial consolidation and the rate of long-term consolidation were developed from laboratory data with which the field measurements show reasonable agreement. It is suggested that the initial consolidation is the result of expulsion of the free water in the peat mass and that the long-term consolidation is the result of expulsion of water contained in the solid peat matter.

ACKNOWLEDGMENTS

The writer would like to acknowledge the assistance and co-operation given by Mr. C. T. Enright and Mr. S. Mikoliew of the Ontario Hydro Hydraulic Generation Department.

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